MAINTENANCE REPAIR WELDING EFFECTS ON THE AXIAL FATIGUE STRENGTH OF AISI 4130 AERONAUTICAL STEEL USED IN A CRITICAL TO THE FLIGHT-SAFETY STRUCTURE

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Abstract. *Critical to the flight-safety welded structures are commonly submitted to several maintenance repairs at the welded joints in order to prolong the in-service life of aircrafts, whose consequence on their structural integrity are not known. The aim of this study was to analyze the effect of successive TIG (Tungsten Inert Gas) welding repairs on the axial fatigue strength of AISI 4130 steel, which is widely used in structures critical to the flight-safety. In order to simulate the cyclic loadings at the welded joints of a specific aircraft component called "motor-cradle", experimental axial fatigue tests were carried out on specimens made from hot-rolled steel plate, 0.89 mm (0.035-in) thick, by means of a INSTRON 8801 equipment, with load ratio R = 0.1, under constant amplitude, at 20 Hz frequency and room temperature. It was observed that the fatigue strength decreases after the TIG welding process application on AISI 4130 steel, with subsequent decreasing due to re-welding sequence as well. Microstructural analyses and microhardness measurements on the base material, heat-affected zone (HAZ) and weld metal, as well as the effects of the weld bead geometry on the results obtained complemented the study.*

Keywords*: fatigue behavior, TIG welded AISI 4130 steel, welding repairs, aeronautic structure, flight-safety.*

1. INTRODUCTION

All over the world the flight safety has been the main concerns for aeronautical authorities. As a result, the accidents index has been at 1.2 for each one million of aircrafts landing/take-off in the occidental world (ANAC, 2003). In general, structural failures during flight are usually attributed to fatigue of materials, project errors or aerodynamic overloads (Goranson, 1993). Since the catastrophic accidents with the English model "Comet" in the 1950's decade, the fatigue process has been the most important project and operational consideration for both civil and military aircrafts (Payne, 1976). Many fractures of materials are caused by fatigue as a consequence of inadequate project or any notch produced during manufacturing or maintenance of aircrafts (Payne, 1976; Wenner, 2000, Latorella, 2000). For several aircraft models (e.g. agricultural, military training and acrobatic) the most solicited and repaired component is the one that supports the motor, called "Motor Cradle" (Fig. 1).

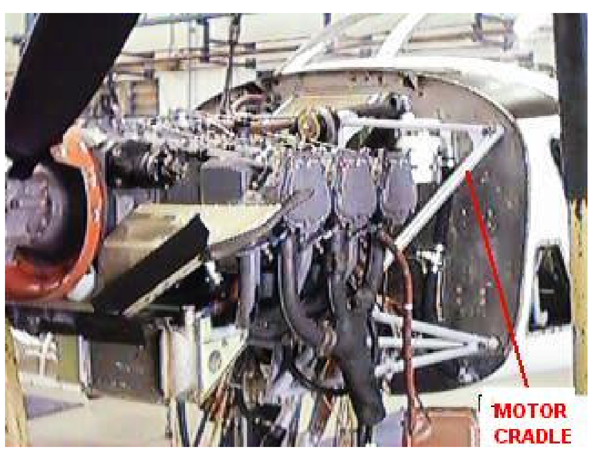


Figure 1: Motor-cradle of the Brazilian aircraft T-25 Universal.

This component presents a geometrically complex structure made from AISI 4130 tubular steel of different dimensions and TIG welded in several angles (Nascimento *et al.*, 2002). For the Brazilian aircraft models T-25 Universal and T-27 Tucano, for example, besides supporting the motor in balance, the motor-cradle also maintain fixed the nose landing gear in the other extremity. As a critical to the flight-safety component, the aeronautic standards are extremely rigid in its manufacturing by imposing a "zero-defect index" on the final weld seam quality (Safe-Life philosophy), which is 100% inspected by non-destructive testing/NDT. For this reason, welded aeronautic structures are frequently subjected to successive repairs in accomplishment to current standards. As a consequence, welded components approved by NDT may contain a welding repair historic report whose effects on their structural integrity are not computed. In addition, these structures are also submitted to weld repairs along their operational life, turning this question more complex. As part of this research work, an investigation on 157 motor-cradle fracture reports indicates that all of them occurred at welded joints as a result of fatigue cracks, by reducing the "Time-Before-Fail" from 4.000 h to 50 h (Nascimento, 2004). Motivated by high fracture incidence of this particular component, an extensive research program to evaluate the fabrication and maintenance weld repair effects on the structural integrity, mechanical properties and microstructural changes has been developed (Nascimento, 2004). Although maintenance repair of parts and components are a multibillion-dollar industry (ASM, 2002), few papers approaching welding repair have been published, being all of them on aged and degenerated materials in petrochemical, offshore and power industries by means of the finite element method (FEM). So, the availability of experimental data of welding repair effects on the structural integrity of aircrafts may be very useful in determining inspection intervals in great-responsibility welded structures. In this paper, special emphasis was attributed to a non-standardized maintenance weld repair procedure, widely employed along the operational life of aircrafts and characterized by overlapping the weld bead by means of gas tungsten arc welding (GTAW) process with filler metal. So, the aim of this particular study was to analyze the effect of successive TIG welding repairs on the axial fatigue strength of AISI 4130 steel carried out on specimens made from hot-rolled steel plate, 0.89 mm (0.035-in) thick. It was observed that the axial fatigue strength decreases after the TIG welding process application on AISI 4130 steel, with subsequent decreasing due to re-welding sequence as well. Microstructural analyses and microhardness measurements on the base material, heat-affected zone (HAZ) and weld metal, as well as the effects of the weld bead geometry on the obtained results complemented the referred study.

2. EXPERIMENTAL PROCEDURE

2.1 Material

For the present research-work flat welded specimens from hot-rolled AISI 4130 aeronautic steel, 0.89 mm (0.035-in) thick, were used. The chemical compositions (%wt) are as follow: 0.32C; 0.57Mn; 0.013P; 0.008S; 0.28Si; 0.18Mo; 0.90Cr; 0.01Cu; 0.02% Ni; 0.057% Al and Fe in balance for the base material, and 0.30C; 0.50Mn; 0.004P; 0.003S; 0.25Si; 0.18Mo; 0.91Cr; 0.042Cu for the weld metal. The mechanical properties obtained from smooth flat samples, in accordance with ASTM E 8M, were: 740.34 ±1.85 MPa for yielding stress (0.2% offset); 809.46 ±2.72 MPa for ultimate strength; 668.79 ±11.47 MPa for rupture stress; 8.48%±1.00 for elongation (in 25 mm length), 0.91 for yielding stress/ultimate strength ratio and 65 HR_A hardness in the "as-received" condition. For original welded specimens with central weld seam crossed to the hot-rolled plate direction the mechanical properties were: 670.8±19.9 MPa for yielding stress (0.2% offset); 778.06±16.87 MPa for ultimate strength; 643.6±26.4 MPa for rupture stress; 3.81%±0.26% for elongation (in 25 mm length), 0.86 for yielding stress/ultimate strength ratio. The monotonic tensile tests were performed by means of a servo-hydraulic INSTRON test machine by applying 0.5 mm/min displacement rate and a pre load equal to 0.1 kN.

2.2 Welding and Re-welding Procedures

The commonly employed welding process for manufacturing of aeronautical structures is Tungsten Inert Gas (TIG), or Gas-Tungsten Arc-Welding (GTAW), which is appropriate to weld thin thickness materials and by allowing necessary control of the existent variables, resulting in high-quality and defect-free weld beads. The TIG welding process was carried out in accordance with EMBRAER NE 40-056 TYPE 1 Standard (for critical to the flight-safety components), with a protective 99.95% purity argon-gas and filler metal AMS 6457 B – Turballoy 4130. A Square Wave TIG 355 – Lincoln equipment was manually employed by an expert aeronautic welder. All the welding parameters were controlled, and the principal ones are indicated in Tab. 1. Yet, all the welded joints were subjected to X-ray non-destructive testing, obtaining approval (sound welds).

Table 1: TIG Welding Parameters.

WELDING POSITION	PLANE
WELDING VOLTAGE	12 V
WELDING CURRENT	40 A
WELDING SPEED	18.0 $cm.min^{-1}$
FLOW RATE	5 $L.min^{-1}$
PRE HEATING	NOT
HEAT INPUT	1.50 $kJ.cm^{-1}$
FILLER METAL DIAMETER	1.6 mm

The welding direction was always crossed to hot-rolling process of the plate. Before welding, the samples were fixed on a device (backing bar) to avoid contamination and porosity in the weld root, and cleaned with chlorinated solvent to oxide removal. After the welding/re-welding process neither subsequent heat treatment to residual stresses relief nor subsequent removal of the final weld bead was carried out, in order to simulate the real condition of the original aeronautic structure. As a consequence of thin plates, only one single-pass was required for original weld. For the overlapping re-welding process, a new single pass was carried out on the previous weld metal. Figure 2 schematically illustrate the repair welding by overlapping, which is usually applied on welded structures along their in-service life. The heat input applied was the same for all the welded and re-welded specimens.

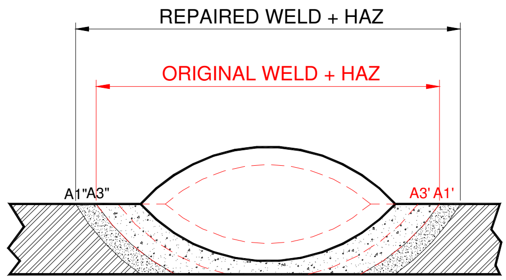


Figure 2: Repair welding process by overlapping the previous weld metal.

2.3 Axial Fatigue Tests.

For axial fatigue experimental tests specimens were manufactured in accordance with ASTM E 466 requirements (Fig. 3), following the LT direction of the plate. The specimens were fatigue tested upon a sinusoidal constant amplitude load, load ratio R = 0.1, at 20 Hz frequency and room temperature. The average superficial roughness, obtained by means of a Mitutoyo 301 equipment with cut-off equal to 0.8 mm x 5 mm, was R_a = 0.73 µm ± 0.12 µm.

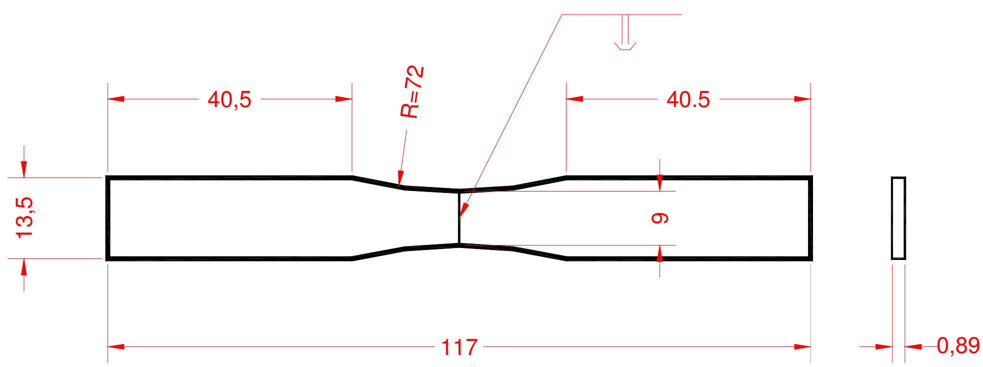


Figure 3: Axial fatigue specimen [mm].

2.4 Microstructural and Microhardness Analyses

For microstructural analysis the chemical etching was made performed Nital 2% during 5 seconds. Vickers microhardness measurements were obtained at 0.0254 mm intervals throughout the regions under analysis (base material, HAZ regions and weld metal) using 1 N load.

3. RESULTS AND DISCUSSION

First of all, it is important to pay attention to the high values of mechanical strength and reasonable ductility from hot-rolled AISI 4130 steel plate. However, it is also interesting to observe the decrease of all that mechanical properties after TIG welding application (from the originally welded specimens), particularly the elongation (fragile). All the monotonic specimens tested fractured at the sub-critical HAZ region (SCHAZ) and base-material interface (strength overmatch).

Figure 4 presents the SN curves of all the specimen conditions tested. The horizontal line indicates the nominal stress value (Sn=247.40 MPa), which corresponds to yielding stress divided by the safety-factor equal to 3 (for critical to the flight-safety welded components), in accordance with the EMBRAER NE 40-056 TYPE 1 Standard.

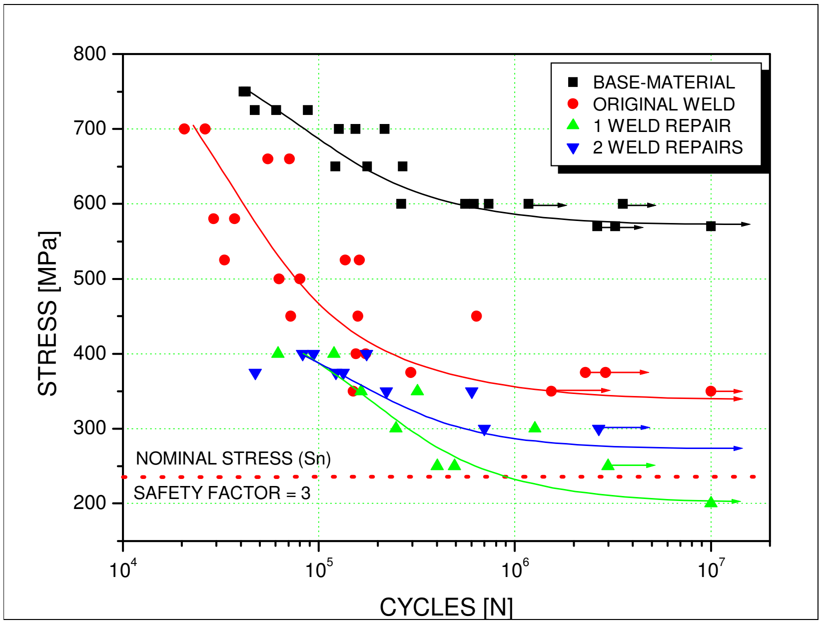


Figure 4: SN axial fatigue curves from base-material and welded specimens subjected to one and two welding repairs.

From Figure 4, one can observe the good behavior in axial fatigue strength of the AISI 4130 steel, whose endurance limit was about 77% of its yielding stress, very above the nominal stress (horizontal line). It is also verified the larger dispersion of the fatigue results obtained from both originally welded and re-welded specimens. This is due to the volume variations of the deposited weld metal that affect the heating/cooling rate and the stress concentration at the weld toe region. Yet, we can observe the subsequent high reduction in axial fatigue strength from welded specimens in comparison with specimen of base material, for both low and high-cycles fatigue regimes (LCF and HCF), whose endurance limit was about 46% of the yielding stress of the base-material. In the high-cycle fatigue regime, it is possible to verify the endurance limit is also located above the horizontal line, which is related to the specified nominal stress (Sn). On the other hand, after the first re-welding application, new subsequent reduction in axial fatigue strength is observed and whose endurance limit in the high-cycle fatigue regime crosses down the Sn line. This behavior is due to the increase in volume of the weld bead with consequent increasing of the stress concentration factor at the weld toe. In addition, the re-welding process can increase the HAZ dimensions and its coarse-grain region (CGHAZ), which is located exactly at the weld-toe and also characterized for still to present considerable hardness and low fracture toughness. So, this implicates that the welding repair strongly commits the structural integrity of this particular welded component, specially considering a critical to the flight-safety component (high-responsibility). Therefore, because the aircrafts are subjected to high fatigue cycles during flight, as a result from abrupt maneuvers, wind bursts, motor vibration and helixes efforts, it is not recommended, or favorable to the flight safety, anyone weld repair application during manufacturing and along the operational life of critical to the flight-safety components. On the other hand, from Fig. 4, we can observe the second re-welding repair resulted in significant increase of fatigue strength, with the endurance limit close the nominal stress value (horizontal line). The higher weld seam volume and consequently lower cooling rate probably tempered the weld metal-CGHAZ microstructures at the weld toe. However, all the axial fatigue (re-)welded specimens fractured at the weld metal-CGHAZ interface (fusion line/weld toe region).

Table 2 presents the microhardness values measured in the three areas of interest (base-material, CGHAZ and weld metal).

Table 2: Vickers microhardness values (HV).

MICROSTRUCTURE	ORIGINAL WELD	1-REPAIR	2-REPAIRS
BASE-MATERIAL	267.7 ± 16.4	285.5 ± 15.8	286.5 ± 19.7
CGHAZ	362.9 ± 55.7	373.4 ± 22.8	477.80 ± 59.15
WELD METAL	573.2 ± 69.8	507.5 ± 47.4	399.9 ± 22.8

From Table 2, one can observe that for both the original weld and one welding repair the microhardness values were close and coherent with each other. This can explains the axial fatigue behavior presented in Fig. 4. However, it is also important to pay attention to the great dispersion of microhardness results in both CGHAZ and weld metal (standarddeviation). It is also possible to observe the highest microhardness value from the original weld metal than for all the other conditions. This implicate that probably the second welding repair promoted the tempering of the previous microstructure, as mentioned early. Additionally, it is also possible to observe the higher microhardness value for the CGHAZ after the second welding repair, by implicating the grain size reduction in that critical region. Yet, it is well-known that the higher hardness the higher fatigue strength.

Figure 5 and Table 3 present the principal geometric factors that compose a weld bead, whose values were obtained by image analysis tool.

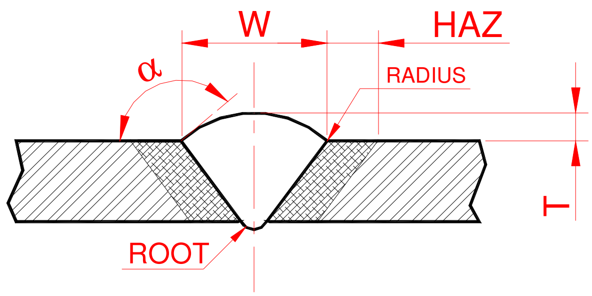


Figure 5: Principal geometric factors from weld profile.

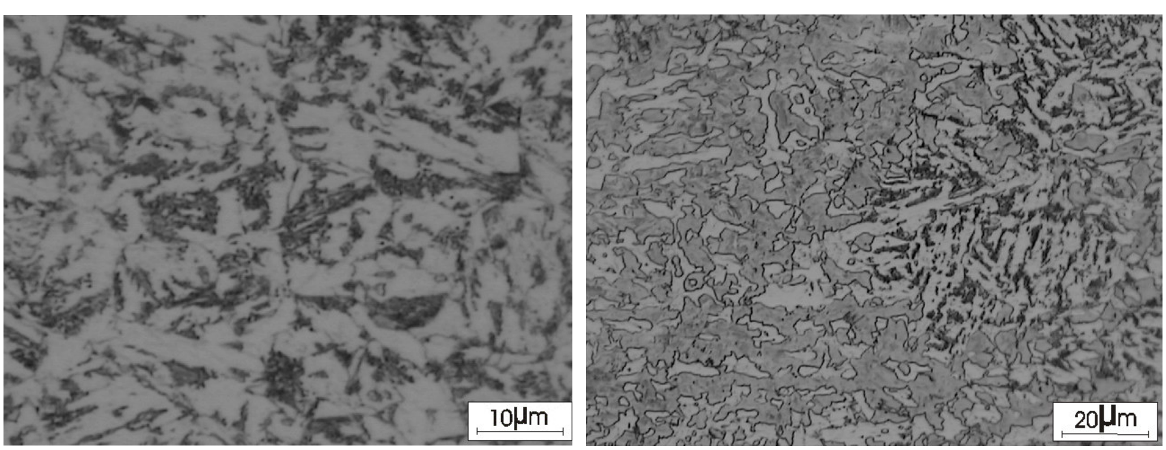
Table 3: Geometric factors from weld profile.

GROUP	W[mm]	T[mm]	ROOT[mm]	ANGLE (α)	RADIUS[mm]	HAZ[mm]	K_t - Eq. (1)
OR	3.75 ± 0.35	0.89 ± 0.20	0.77 ± 0.19	141.95° ±14.40°	1.03 ± 0.36	2.89 ± 0.25	1.290
1R	4.49 ± 0.33	1.17 ± 0.32	0.82 ± 0.27	146.09° ± 8.62°	0.75 ± 0.21	3.11 ± 0.12	1.305
2R	4.80 ± 0.23	0.96 ± 0.20	0.79 ± 0.30	138.64° ± 7.52°	0.93 ± 0.40	3.22 ± 0.23	2.178

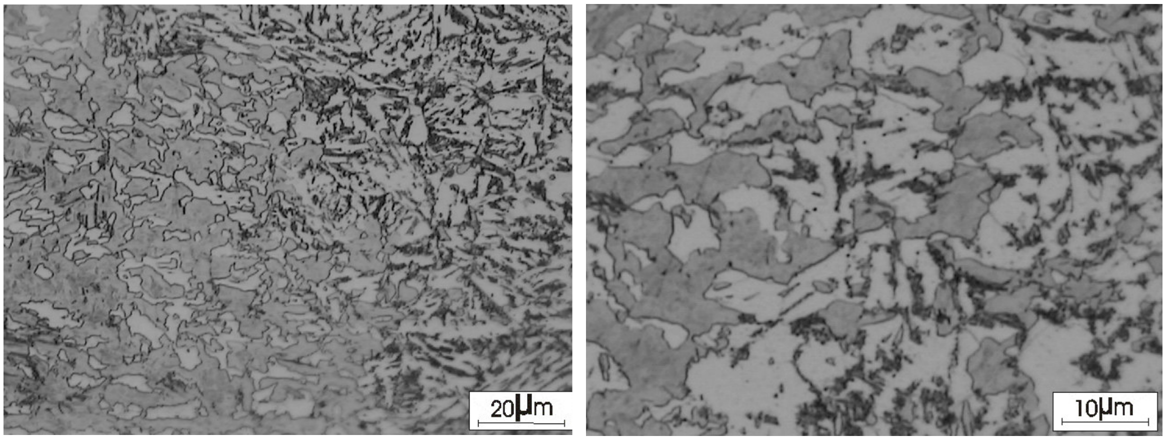
where: $$K_f = 1 + \frac{K_t - 1}{1 + a/r} \qquad (1)$$

a=0.1659 (Peterson's material parameter for steel); r= notch-root; K_f = fatigue-notch factor.

From Table 3, it is possible to confirm all the results presented in Fig. 4, i.e. the effect of welding repairs on the axial fatigue behavior of AISI 4130 steel. So, it can be observed that the welding repairs reduced both the angle (α) and the radius on the weld toe, which are considered the principal geometric factors controlling the fatigue behavior of welded components and structures (Lancaster, 1999; Nascimento, 2004). In addition, the high scatter on the geometric factors measured is in accordance with the high scatter of the fatigue results presented by the welded specimen groups. Yet, from Tab. 3, we can observe: the increase of the stress concentration factor, Kt (Peterson, 1966), at the weld toe with the successive welding repairs; the largest extension of HAZ due to the successive heat-input applied and, consequently, the increase of the CGHAZ as well; the effect of both weld bead (T) and weld root dimensions, again, on the angle (α) and radius reduction and, consequently, on the axial fatigue strength of welded specimens. Figures 6 and 7 present the base-material, HAZ and weld metal microstructures for all the proposed conditions.



(a) Base-material (typical). (b) Sub-critical HAZ – A1 – Original weld.

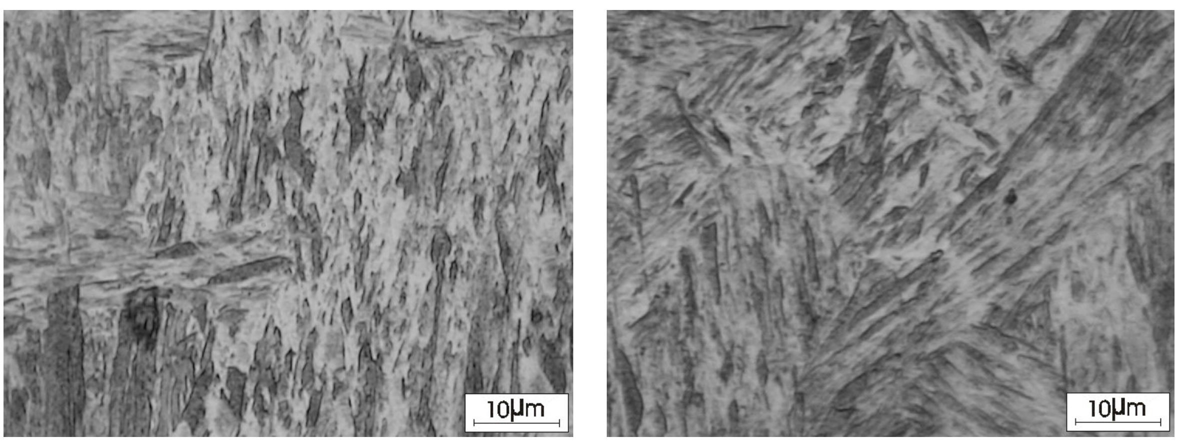


(c) Sub-critical HAZ – A1 - One welding repair (d) Sub-critical HAZ – A1 - Two welding repairs

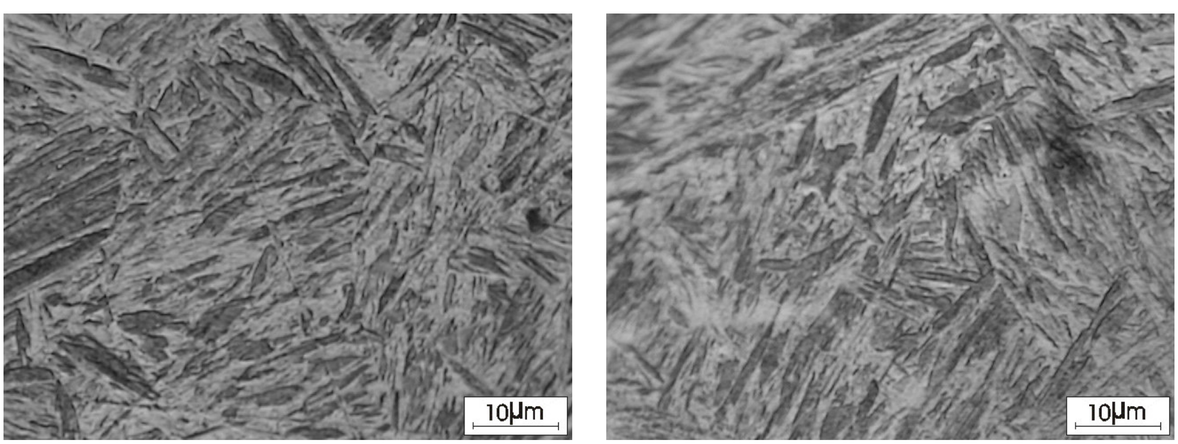
Figure 6: Base-material and base-material/HAZ transition microstructures. Nital 2%.

Figure 6(a) shows the normal products of transformation from austenite, i.e. ferrite and perlite. In Figures 6(b), 6(c) and 6(d) the beginning of the transformation from perlite to austenite is observed (to martensite, in the subsequent cooling).

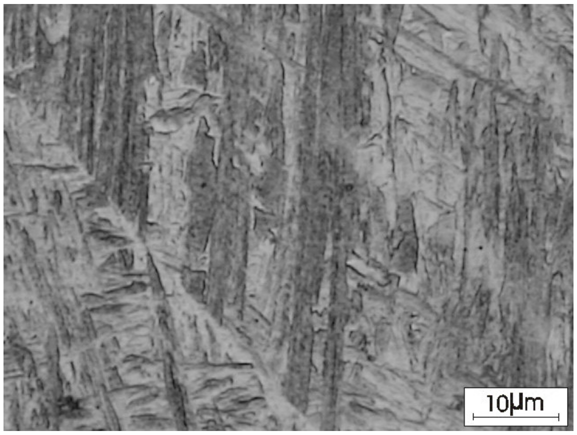
Figure 7 presents the constituents of the weld metal (original, one and two re-welding) and CGHAZ related, which are basically constituted by martensite.



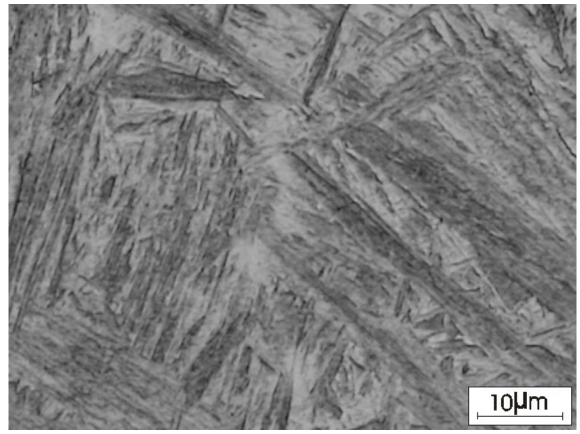
(a) Original CGHAZ (b) Original Weld Metal



(c) CGHAZ from the first welding repair. (d) Weld Metal from the first welding repair.



(e) CGHAZ from the second welding repair.



(f) Weld Metal from the second welding repair.

Figure 7: Microscopic analysis from the welding regions. Nital 2%.

4. CONCLUSIONS

Motivated by high fracture incidence at welded joints of a specific component critical to the flight-safety, called "motor-cradle", experimental axial fatigue tests on welded and re-welded specimens were carried out. Based on the results obtained, the following conclusions may be drawn:

1 –The AISI 4130 steel possess good mechanical properties and endurance limit when subjected to axial fatigue, and reasonable elongation in the "as-received" condition (not heat-treated). However, the TIG welding process with filler metal reduced all the mechanical properties of the AISI 4130 steel, in special the elongation.

2 - All the monotonic specimens tested fractured at the sub-critical HAZ region (SCHAZ) and base-material interface (strength overmatch).

3 - The TIG welding process decreased the axial fatigue strength of the AISI 4130 steel as well, as in low-cycle as in high-cycle of fatigue (LCF and HCF) regimes.

4 – It was verified the high scatter of the fatigue results obtained from both originally welded and re-welded specimens.

5 - After the first re-welding application, new subsequent reduction in axial fatigue strength was observed and whose endurance limit in the high-cycle fatigue regime crosses down the Sn line (about 30% of the yielding stress from base-material). This implicates that the welding repair strongly commits the structural integrity of this particular welded component, specially considering a critical to the flight-safety component (high-responsibility).

6 - Because the aircrafts are subjected to high fatigue cycles during flight, as a result from abrupt maneuvers, wind bursts, motor vibration and helixes efforts, it is not recommended, or favorable to the flight safety, anyone weld repair application, as much for manufacturing as along the operational life of critical to the flight-safety components.

7 – However, the second re-welding repair resulted in significant increase of fatigue strength, with the endurance limit close the nominal stress value (horizontal line), but still critical to the flight-safety of the aircraft.

8 - All the axial fatigue (re-)welded specimens fractured at the weld metal-CGHAZ interface (fusion line/weld toe region).

9 - It was observed high scatter on the fatigue strength values obtained with the (re-)welded specimens, in correspondence with the high scatter of the geometric factors measured from the weld profile.

10 - The axial fatigue behavior of the (re-)welded specimens was most affected by the microstructural and microhardness variations and, mainly, the geometry of the weld bead, typically the angle and radius correlation at the weld toe.

5. ACKNOWLEDGEMENTS

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